

Primordial black holes, phase transitions, and the fate of the universe^{*}

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Abstract. Phase transitions in the early universe are prime settings for the production of primordial black holes, since they can break the relatively quiescent homogeneity and isotropy of Friedmann–Robertson–Walker (FRW) cosmologies. These epochs of “symmetry breaking,” moreover, can affect the subsequent development of spacetime by changing the evolution of some FRW parameters, including the present age and density of the universe. We discuss the relative importance of such effects on constraining mechanisms of black hole formation.

1. Introduction

Although they have not yet been observed, primordial black holes (PBHs) already deserve a special place in the temple of modern theoretical physics, for they have spawned many creative ideas at the intersection of cosmology, astrophysics, and particle physics. In cosmology, for example, they may affect the outcome of Big Bang nucleosynthesis (BBN) [1]. Primordial black holes may be of astrophysical interest through their evaporative production of the highest energy cosmic rays [2]. Their formation during cosmic phase transitions (e.g., the electroweak (EW) and quantum chromodynamic (QCD) transitions) also may help constrain the relevant particle physics. Further examples of this rich spectrum of applications abound in these proceedings. We consider below the example of Massive Compact Halo Object (MACHO) black holes and discuss two bulk cosmological constraints on the production of such holes.

2. An example: MACHO black holes formed at the QCD epoch

One of the recent uses of PBHs involves the dark matter in the halo of our Galaxy. The MACHO Project reports that the Galactic halo contains condensed objects of about 0.2 to 0.8 solar masses [3]. Since candidates such as ordinary stars, white dwarfs, neutron stars, etc., are constrained by various observations such as the Hubble Deep Field, stellar and cosmological nucleosynthesis, etc., we must consider more exotic possibilities to explain the MACHO events. Primordial black holes evade these constraints, because they would have formed in the early universe before BBN.

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In order to produce MACHO-sized black holes, the existence of particle horizons requires that we study an epoch during which a horizon volume contains at least about one solar mass in mass-energy. The early universe is characterized by a very high degree of homogeneity and isotropy of spacetime. Further, any isocurvature fluctuations larger than a horizon length are “frozen,” and those smaller are damped. The only reasonable way to produce PBHs, therefore, must involve the amplification of pre-existing curvature fluctuations (those laid down by inflation, for example) or the creation of such perturbations as a result of phase transitions (PTs). Typical first-order PTs, however, nucleate bubbles of the broken phase that are small compared to the horizon, so they cannot make MACHO-sized black holes. Second-order PTs have even less spectacular consequences, so we focus on the possibility that a first-order PT amplifies pre-existing fluctuations to the point of gravitational collapse into roughly horizon-sized black holes. Since the mass in the horizon at the QCD epoch is roughly one solar mass, there is a chance that some horizon volumes will “go down” into MACHO-sized black holes during or just after the QCD transition (see, for example, Ref. [4] for detailed discussions of specific formation mechanisms).

3. Two constraints on PBH formation

The mechanism of black hole formation had better not be too efficient, for energy density in black holes redshifts like ordinary matter (i.e., more slowly than radiation), and copious PBH production would make the universe prematurely dominated by non-relativistic matter, precluding crucial cosmological events like BBN. Another way to state this is that the universe becomes “overclosed” (i.e., Ω_{PBH} today is inconsistent with the present observational bounds on Ω_0) unless there is at most one PBH formed per 10^7 horizon volumes [5]. This is a powerful constraint on building models of PBH formation.

Another possible constraint involves the manifest breaking of Friedmann–Robertson–Walker (FRW) symmetry when a PBH forms. Using the previous constraint, we can view the universe as a lattice of comoving black holes with a lattice separation of at least ≈ 215 horizons at the epoch of formation. The horizon eventually expands to encompass many holes, at which time they may attract each other and cluster together. Since black holes are the ultimate curvature fluctuations, spacetime expands non-uniformly, and the overall Hubble expansion of the universe is valid only in an averaged sense. In particular, these fluctuations effect a “back-reaction” on the expansion of the universe and may change the values of Ω_0 and H_0 observed today (i.e., the fate of the universe). If the resulting theoretical values disagree significantly with the current values, then this is a valid constraint on PBH formation.

The latter constraint is quantitatively calculable using a general relativistic perturbation theory in a suitable gauge but, with minimal perspiration, we can conclude that this effect is utterly negligible. First, we expect the effect of inhomogeneities on the expansion or age of the universe to be more significant during the epoch of matter domination than radiation domination, since the former lasts much longer than the latter and since nonlinear structures such as galaxies and clusters may form only during the former epoch. Using a general relativistic analog of Zel’dovich’s pancake approximation for gravitational collapse, Russ and collaborators [6] have calculated the change in the age of the universe due to growing inhomogeneities. They find that the age of the universe decreases from the usual FRW value by a part in 10^3 to 10^4 , depending

on the composition of the dark matter. Therefore, the potential constraint on PBH production described in the previous paragraph is *very* weak. To put it another way: the constraint may become important only when we know the age of the universe to at least three significant figures.

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